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POWER FOR LUNAR SURFACE MINING

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POWER FOR LUNAR SURFACE MINING

I. Introduction

Just as in the case of earth surface mining, the basic choice of a power system for lunar mining appears to be between individual units for each machine or operation and a central system with distribution through trailing cables. In either case, power will undoubtedly be electric 1, 2, 3/. Heat engines, either internal or external, are unsuitable for lunar condition 1,3/, and their fuels must be transported from earth unless they, too, can be found or manufactured on the moon.

To date, most of the published material on space power systems has dealt primarily with power for space craft 1,4,5,6/, with some references to early lunar landings. At least one paper discusses nuclear thermionic lunar base power 7/. Mining and processing operations near a lunar base would be certain to add substantially to power requirements and may, indeed, become the principal power load.

Fig. 1 1/ shows, diagramically, the various possible power sources and conversion devices. Chemical and solar systems have been used successfully on spacecraft but large power requirements may depend upon nuclear or solar concentrator systems.

Fig. 2 1/, shows the approximate range of power levels, as related to lifetimes, for various space power systems. It will be noted that there is no lifetime limit on solar or nuclear systems but only the nuclear system has a high (>∿10 kw) power output. On the lunar surface, chemical-mechanical, fuel cells and batteries would not have the restricted time limits shown in Fig. 1 if (a) a continuous supply of fuel could be fed to a chemical-mechanical system, (b) fuel cells are made regenerative and (c) batteries are continuously or regularly recharged. Radioisotope systems would have approximately the lifetime limits shown, on the lunar surface. Bucher 1/ says: "It may be seen that for relatively low power levels and long lifetimes, the solar photovoltoic system is useful. For slightly higher power levels and moderate lifetimes, the nuclear radioisotope battery with thermoelectric or thermionic conversion is desirable. For longer lifetimes in approximately the same power range, solar concentrator systems with thermoelectric or thermionic conversion gain favor. At higher power levels, with moderate to long lifetimes, the solar mechanical or solar-thermionic systems become attractive. And finally, at the highest power levels the nuclear fission mechanical or the nuclear thermionic systems are most efficient."

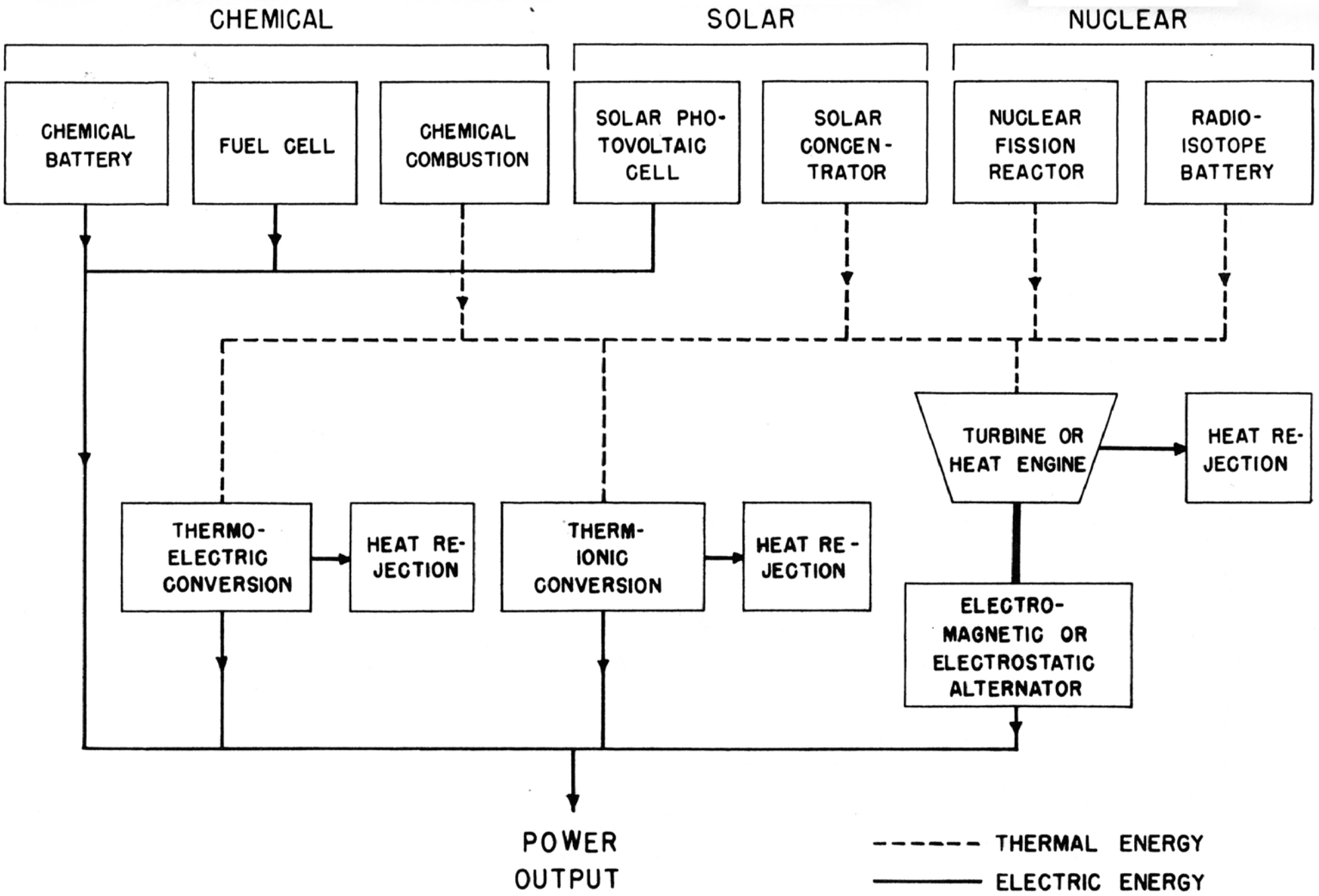

Figure 1. Power sources and conversion devices. Dashed arrows - thermal energy; solid arrows - electric energy 1/.

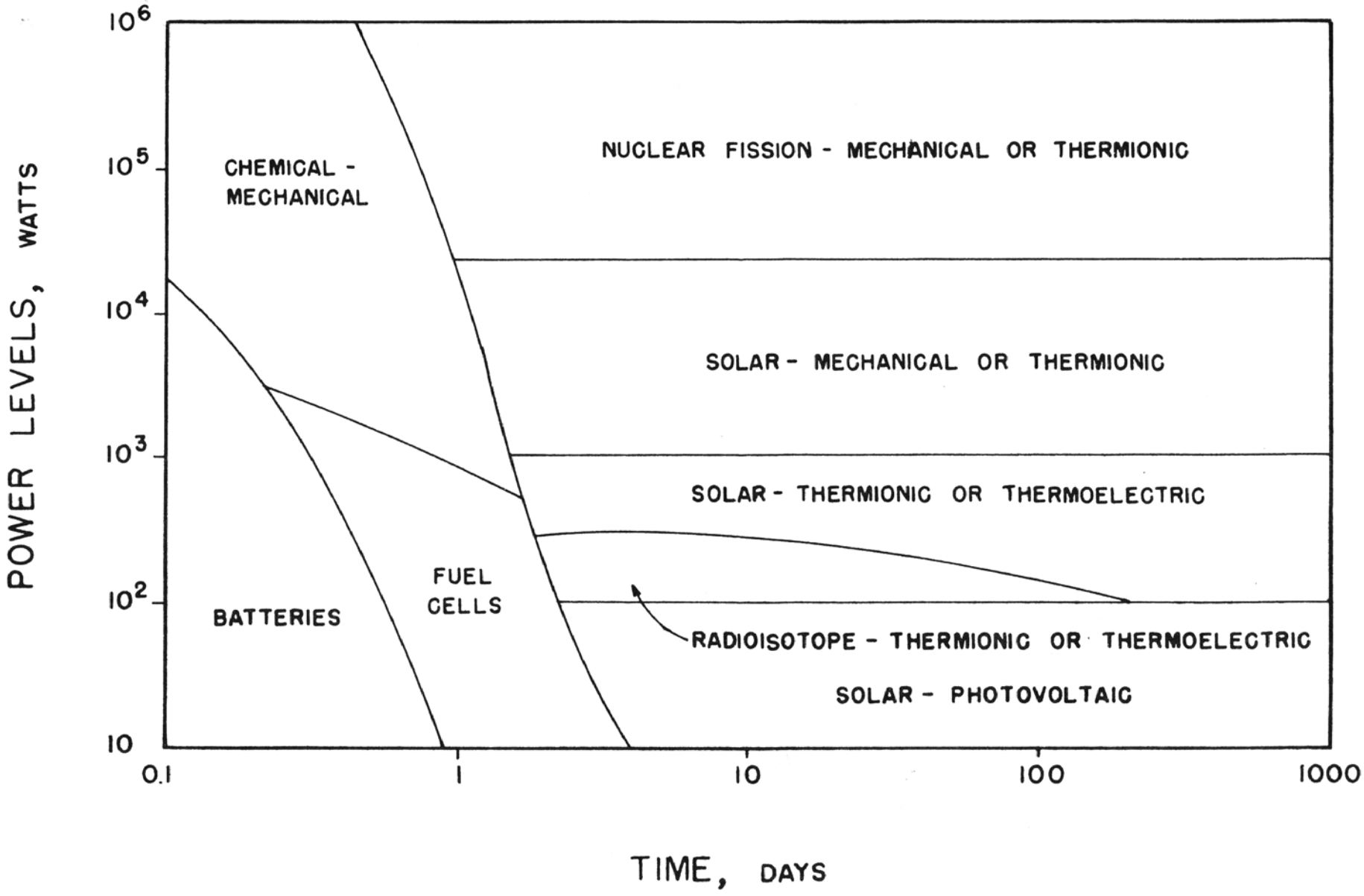

Figure 2. Space power systems for various power levels and lifetimes 1/.

The size of the power demand for minimg is not easy to estimate. The motor horsepower ratings of selected models of earth-based, light strip mining equipment were found to be under 186.5 kw (250 horsepower). Modification of weight of the selected units for lunar use by incorporation of parts made from lightweight metals and alloys should substantially reduce weight requirements. For use on the moon, ballast or counterweights of local origin can be placed on equipment to add mass, if such addition is needed. Power required on the moon for lifting loads at earth speeds should be only 1/6 of earth values. Locomotion requirements may not be reduced that much, however, if there is significant vacuum adhesion of lunar surface particles or if the bearing strength of the lunar surface, in places, is low and allows considerable sinkage of treads or wheels.

Probably the governing factor on power requirements for lunar mining equipment will be that required for digging. If lunar rock or soil is as tough and adherent as is earth soil and rock, power requirement at constant speed may be equal to those on earth. In any case, requirements should lie between 1/6 and full earth values. From studies of Surveyor data 8-12/, it appears doubtful if there is enough lunar vacuum adhesion to require more digging power than on earth. If we select a compromise figure of one-half earth power, maximum requirements are reduced to 125 horsepower on the moon or 93,250 watts or 93.3 kw. The power requirement for presently envisioned surface mining operations (including no power for processing) might conservatively be set at 100 kw (134 HP). From Fig. 2, it is seen that 10^5 watt loads virtually rule out systems other than chemical-mechnical or nuclear fission. With enough concentrating mirrors, a solar concentration-mechanical system might be brought to this level also but its impotence during the lunar night would seem to make it impractical.

II. Power Source

Levedahl reports on the development of a 100-kw(e) nuclear-thermionic power plant 7/. He says: "In both the intermediate and advanced stages of (Apollo) operation, only nuclear power plants appear capable of providing the very large quantities of energy necessary, and these plants must fit within the weight, size and center-of-gravity limitations of the advanced Saturn and Lunar Logistics Vehicle. Of the several types of nuclear power plants which have been studied, the thermionic nuclear reactor system has many advantages which uniquely qualify it for lunar power application." As quasi-permanent bases have been suggested for as early as 1975 13/, 1985 power requirements should be well beyond a single power plant of the capacity Levedahl discusses.

The suggested lunar installation of the power plant is shown in Fig. 3 7/, in a lunar depression or crater. A suitable crater, requiring little or no modification, should be located a short to moderate distance from almost any mining area. A depth of 10 feet or more below the surface will protect men on the surface who are not too close to the nuclear plant. A raised crater edge will provide perfect shielding, in the absence of any atmosphere, to reflect nuclear radiation to personnel on the surface. In addition, if reflectors are placed on both the inside and outside surfaces of the radiator, heat rejection capacity is greatly increased, exceeding by 60% a single surface in outer space 7/.

The power conditioning system, as shown in Fig. 3 7/, can be external to the power plant and can tailor frequency and voltage and/or convert to AC, as may be needed for mining operations. If the plant also powers a lunar base or a processing operation, requiring different power conditions, this unit, or units, can provide for both requirements.

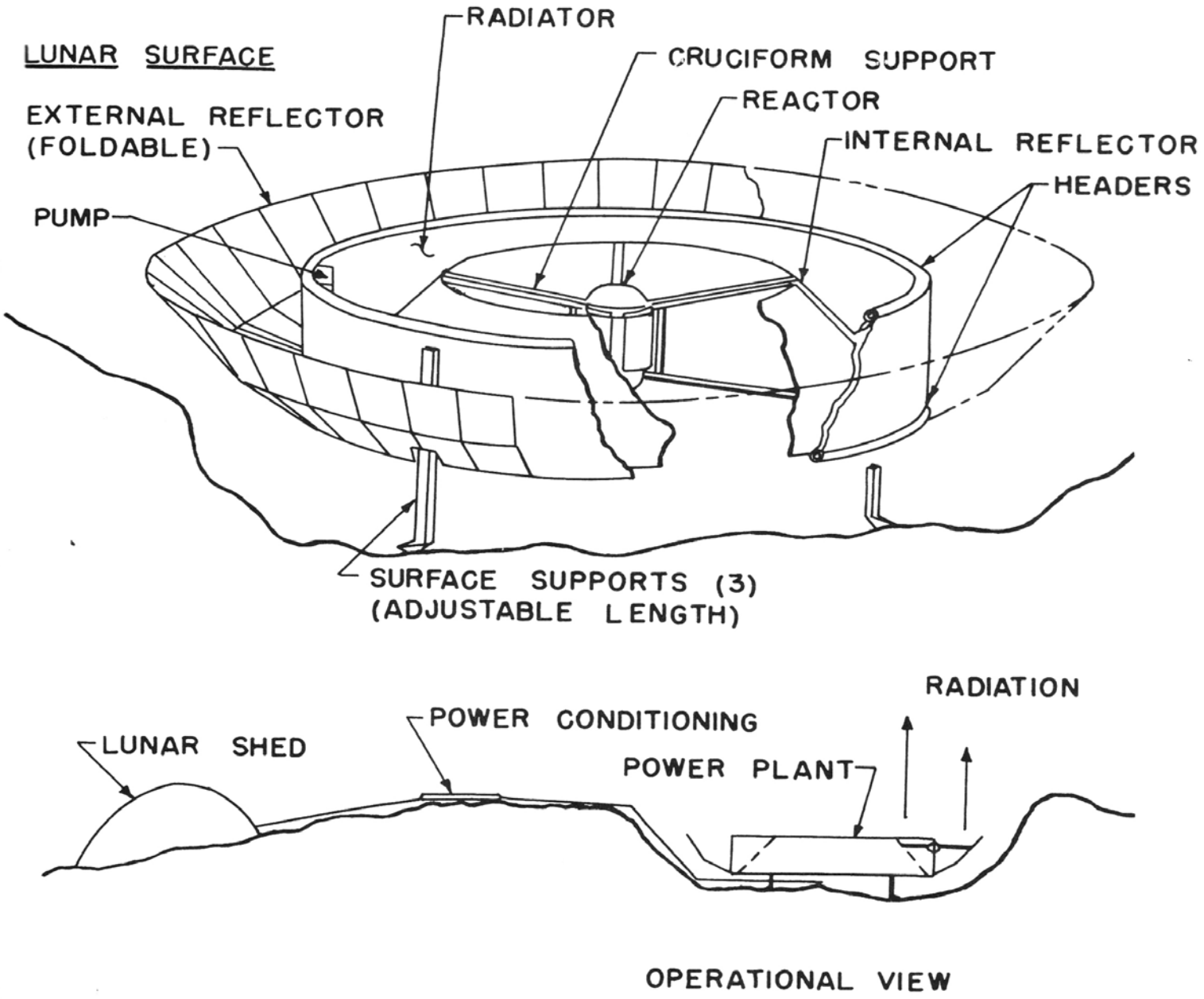

Figure 3. Lunar power plant concept 7/.

Because of the development of higher voltages, the flexibility provided and the possibility of incorporating d-c/a-c power converts into the power conditioning equipment, the thermionic nuclear power plant 7/ would prove the most satisfactory source for the type and quantity of power needed for the scale of mining operation envisioned.

It is beyond the scope of the current work to go further into the power source problem but Levedahl suggests that the system he describes could be developed in about five years from go-ahead and at a cost, including fabrication of 2 or 3 operational systems, less than that of transportation of one lunar logistic vehicle to the surface of the moon 7/.

III. AC or DC Power?

Electrical power for earth-based surface mining operations is almost always alternating current. It may prove desirable to use AC in lunar operations.

If individual power generators are used on mobile machines, however, it is almost certain that DC will be generated. "Currently our most developed schemes such as fuel cells generate direct current" 14/. Bucher 1/ states that "One disadvantage of the fuel cell is the low voltage D-C output. For high voltages, cells may be placed in series, or d-c/a-c converters can be used." All chemical and solar systems, except chemical-combustion or solar concentrator systems, would have similar characteristics.

Although d-c power is probably used in all space vehicles to date 5/, it is unlikely that type will be satisfactory for mining operations on the scale being investigated. A representative of an electrical manufacture writes: "In all probability, direct current motors will not be used because of the difficulty of providing an artificial environment for commutation and insulation effect. - - - one might envision a DC motor as having to be 'canned' in oil in order to operate in a deep space environment. The problems of sealing, connections and weight-to-power ratio would become obvious, using this technique." 3/. Another company representative writes that: "Lifetime of motor brushes would pose a problem in the lunar vacuum" 12/. Work has been done on the development of brushless DC motors but "most of the present brushless DC motor designs for space vehicles are limited to output power levels of a few hundred watts" 5/. Hope was expressed for improvement in design but application in space vehicles is still the use referred to. Some success has also been achieved in the development of a long-life brushes for vacuum use 15/.

A-C current apparently would be easier to handle and more flexible. "We have had some experience trying to make a small motor - - - using the approach of sealed, oil-cooled commutator-type d-c motor operating from a fuel cell. The approach may be satisfactory for very limited, short-time operations, but any major mining operation would require the use of an a-c motor" 14/.

IV. Central Distribution vs Individual Power Units

If lunar mining is done by drilling, requiring moving from one location to another 16/ or by the use of relatively small equipment units such as bulldozers or front-end loaders, operating singly in small deposits or in multiples, in large ones 2/, there might be some advantage in having individual power sources for each machine. If so, the fuel cell appears to be the most promising unit. It seems likely, however, that further development of this source is necessary before its use becomes possible. "Until some larger power supply other than the Apollo-type fuel cell is available, motor ratings will be limited to 5 HP or less. A much more satisfactory system would use an inverter and an a-c motor, both of which would have to be hermetically sealed and cooled with a radiator and either circulating gas or oil. - - - motors of the larger sizes you mentioned would undoubtedly have to be a-c operated from a nuclear power plant - - - " 14/. Only the very smallest of bulldozers or front-end loaders investigated and the existence of very favorable lightness and looseness in lunar materials, would permit operation at 5 HP or less. One small rubber-tired front-end loader manufacturer advertises a 15.5 and 24 HP (11.6 and 17.9 kw) model with a 1000 bl. load capacity. With sand weighing 1760 kg/m^3 (110 lb/ft^3), this gives a volumetric capacity of only 0.26 m^3 (9.1 ft^3 or 1/3 yd^3). If lifting is the most difficult task in lunar mining operations, motors of 1.94 and 2.98 kw (2.6 and 4.0 HP) rating, respectively, should provide sufficient power. In this case, however, the machine would handle an entirely inadequate volume of ore and overburden per shift, to meet a large or moderate water demand 2/.

Although small tractors, propelled by individual power units, will be indispensible for the mobility required for lunar exploration and for interbase travel, it now appears that they will not be too useful as mining equipment

unless considerable progress can be made in the development of higher capacity, efficient power sources.

This conclusion leaves fixed equipment powered by larger a-c motors or mobile equipment, also powered by a-c motors and with current supplied through the lunar surface or by trolly wires or tracks or by trailing cables. Supplying current through the lunar surface probably will be entirely too inefficient even though the lunar surface may be more conductive than the earth's. Tracks, monorails and trollys restrict mobility severely. Trailing insulated conductors on the ground restrict radius of mobility, but provide excellent mobility within the designed radius.

In addition to problems connected with size and length of cable, there will also be problems of temperature and materials. At 104-122° K 2/ it is almost certain that earth-designed cable materials will be too brittle and inflexible. More satisfactory materials may be developed that will insure sufficient flexibility and wear resistance, or (1) materials may be used that are suitable at lunar night temperatures but which must be coiled and stored in darkness during the lunar day or (2) earth-design materials may be used but with heating coils added so as to maintain the cable at a temperature at which it is not too brittle and inflexible. The latter solution would, of course, increase power consumption.

Centrally controlled rope-and-scraper systems would not require cables. Cables could be used with power shovel, dragline, scraper-loader, front-end loader, hoe or bulldozer systems 2/. Multiple unit systems would require multiple cables and thus increase system weight and complexity. With cable power distribution, sufficiently large conductors could insure reasonably economic use of low voltage d-c as well as high voltage a-c power, but cable costs would be greater.

Although parts of the lunar surface "seen" in small scale by Surveyor probes have rather gentle slopes 8-12/, there are enough depressions and loose boulders that the surface may be quite abrasive to trailing cables. Until some "lunarock" is actually examined, however, no estimate of its abrasiveness can be made.

V. Weight Relations

In previous studies 2, 17/, it was thought possible that significant savings in equipment weight might be effected for postulated lunar designs over earth-designed models by replacing diesel and gasoline motors with electric motors. It was concluded that, while some weight savings may be made, the demands of the lunar environment may result in such reductions being small to moderate.

Motor frames are about the only place where substitution of light metals such as Be, Al or Ti can be made. The light metals generally do not have electrical properties suitable for substitution in the electrical parts of the motors or for shafts, bearings, etc.

The necessity for disposing of the heat generated by operating electric motors will add to their weight. Light fluids can be used and radiators, pumps and plumbing can be made of light metals but the requirement of integral cooling systems on all motors will add weight not required on earth.

Heat rejection systems may use liquid, vapor-liquid or gaseous working fluids. The liquid-vapor system has some advantages over the other two: however, the gas system is quite similar to liquid-vapor. It is simpler and may be multipurpose, including lubricating bearings, cooling rotating machinery and actuating pressure devices 1/. Some advantages stated for liquid-vapor systems over liquid systems are (1) a smaller inventory of working fluid is needed because of the relatively large quantity of heat released by the fluid phase charges. (2) The vapor can be raised to a higher temperature than boiling. (3) The overall heat coefficient is higher for liquid-vapor. (4) Not only is more fluid required by a liquid system but the heat rejector and plumbing to handle the fluid must be heavier. In comparison to a gaseous system, the vapor system is (1) lighter and requires less radiator area because of greater capacity per pound of fluid. (2) In a gas system, higher temperatures and higher pressures create more material and engineering problems 1/.

One disadvantage of the vapor system for space vehicles is that it has the problem of condensing in a nongravity condition. This condition will not exist on the lunar surface. The lunar gravity is much lower than on earth, but this should not result in operation any different from on earth.

The characteristics of the possible working fluids for either system will have an important bearing on any comparison of liquid-vapor and gaseous systems 1/.

Information collected on gasoline and diesel motors yielded a weight ranging from 535 to 2520 pounds for bulldozers and front-end loaders. For draglines and shovels, the range was from 4565 to 6620 pounds. There are undoubtedly models of similar capacities to these that will run a little heavier or a little lighter. The manufacturers of some of the heavier shovels and draglines considered, did not furnish motor weights.

Electric motors vary widely in weight with type and anticipated use. A representative of an electrical machinery manufacturer suggested a possibly attainable scale for a-c motors as follows 3/:

0.75-3.7 kw	(1-5 HP)	about 0.33 kg/kw	or 2.0 lb/HP	= 0.9-4.5 kg	(2-10 lb)
7.5-38.3 kw	(10-50 HP)	0.17 kg/kw	1.0 lb/HP	4.5-22.7 kg	(10-50 lb)
37.3-149.2 kw	(50-200 HP)	0.13 kg/kw	3/4 lb/HP	17.0-68.0 kg	(37.5-150 l
>186.5 kw	(>250 HP), wt/HP ratio passes optimum and mechanical problems associated with physical size cause it to increase.				

Data furnished by another manufacturer 12/ gives, for 60 cycle induction motors, 230 volts at full load current, ∿1800 rpm speed, drip-proof enclosures:

KW	HP	WEIGHT	WT/HP
0.75	1	13.6 kg (30 lbs)	18.1 kg/kw (30 lb/HP)
3.73	5	31.8 kg (70 lbs)	8.5 kg/kw (14 lb/HP)
7.4	10	64.0 kg (141 lbs)	8.6 kg/kw (14.1 lb/HP)
37.3	50	181.4 kg (400 lbs)	4.9 kg/kw (8.0 lb/HP
74.6	100	367.4 kg (810 lbs)	4.9 kg/kw (8.1 lb/HP)
111.9	150	542.1 kg (1195 lbs)	4.8 kg.kw (8.0 lb/HP)

Standard DC motors, drip-proof enclosures, 240 volts DC:

KW	HP	WEIGHT	WEIGHT/HP
0.75	1	31.8 kg (70 lbs)	42.4 kg/kw (70 lbs/HP)
3.73	5	63.5 kg (140 lbs)	17.0 kg/kw (28 lbs/HP)
7.46	10	147.4 kg (325 lbs)	19.8 kg/kw (32.5 lbs/HP)
37.3	50	394.6 kg (870 lbs)	10.6 kg/kw (17.4 lbs/HP)
74.6	100	598.8 kg (1320 lbs)	8.0 kg/kw (13.2 lbs/HP)
111.9	150	859.6 kg (1895 lbs)	7.7 kg/kw (12.6 lbs/HP)
186.5	250	1324.5 kg (2920 lbs)	7.1 kg/kw (11.7 lbs/HP)

There is a great contrast in the weight/HP ratios from the two manufacturers. Undoubtedly, the reason is that the information from the first manufacturer came largely from the aerospace electircal division and probably reflects experience in design of light motors for spacecraft and other weight-saving uses, thus representing the best yet achieved. Furthermore, the weights given may not include such things as drip-proof enclosures or totally enclosed motors, but refer to the bare working motor itself. The second manufacturer simply furnished data on earth-designed motors actually being used in industry. It is excellent that we have both sets of ratios. Rugged motors, designed for mining, probably cannot reach the most favorable ratios above, but the ratios in common industrial use on earth where weight is a factor usually subordinate to efficiency, manufacturing cost and specific utility, should be surpassed.

It will be noted that for similar capacities, presently used industrial a-c motors have more favorable weight-horsepower ratios than do d-c motors. In general, for the same horsepower rating, d-c motors have ratios about 133 percent greater than those of a-c motors up to 37.3 kw (50 HP) and about 50 percent more, in the case of the larger motors.

It seems reasonable to postulate that a-c motors, designed for use in lunar mining machinery in the 7.5-112.0 kw (10-150 horsepower) range, might be designed to achieve a ratio of about 3.0 kg/kw (5 lbs per horsepower, not including the weight of heat rejection systems or of hermetically sealed bearings housings,

etc. This would give weights of from 23-336 kg (50-750 lbs), significantly less than those of equally rated gasoline and diesel motors. Part of this savings will be offset by heat rejection systems, etc. Heat engines in use on earth have heat rejection or cooling systems but if they were to be used on the moon, these systems might have to be heavier and more elaborate, further adding to their weight.

Because of the probable small size of saving to be effected by change in motive power of earth equipment designs from heat engines, this factor may be omitted in the estimation of weight reduction factors for equipment designed for lunar use.

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